

# Electromagnetic Signals at SPS and RHIC

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# Outline

## 1. Photons at SPS

- Hadron gas contribution (massive Yang-Mills approach)
- prompt contribution ( with Cronin effect evaluation)
- comparison to WA98 data

## 2. Photons at RHIC

- jet energy loss (Arnold-Moore-Yaffe formalism)
- direct jet-photon production in QGP
- other photons sources in Au-Au
- comparison with PHENIX data

## 3. Summary and outlook

# 1. SPS

## 1.a) Hadronic production rate

From relativistic kinetic theory, the production rate for the process  $1 + 2 \rightarrow 3 + \gamma$  is:

$$q_0 \frac{dR}{d^3q} = \int \frac{d^3p_1}{2(2\pi)^3 E_1} \frac{d^3p_2}{2(2\pi)^3 E_2} \frac{d^3p_3}{2(2\pi)^3 E_3} (2\pi)^4 \delta^{(4)}(p_1 + p_2 \rightarrow p_3 + q) |M|^2 \frac{f(E_1)f(E_2)[1 \pm f(E_3)]}{2(2\pi)^3} \quad (1)$$

### Calculation of $M$ :

- The interactions of any hadrons are described by  $\mathcal{L}_{\text{eff}}$
- $\mathcal{L}_{\text{eff}}$  should respect chiral  $U(3)_L \times U(3)_R$  symmetry.

# Non-linear sigma model:

(H. Gomm, Ö. Kaymakcalan, and J. Schechter, Phys. Rev. **D30**, 2345 (1984))

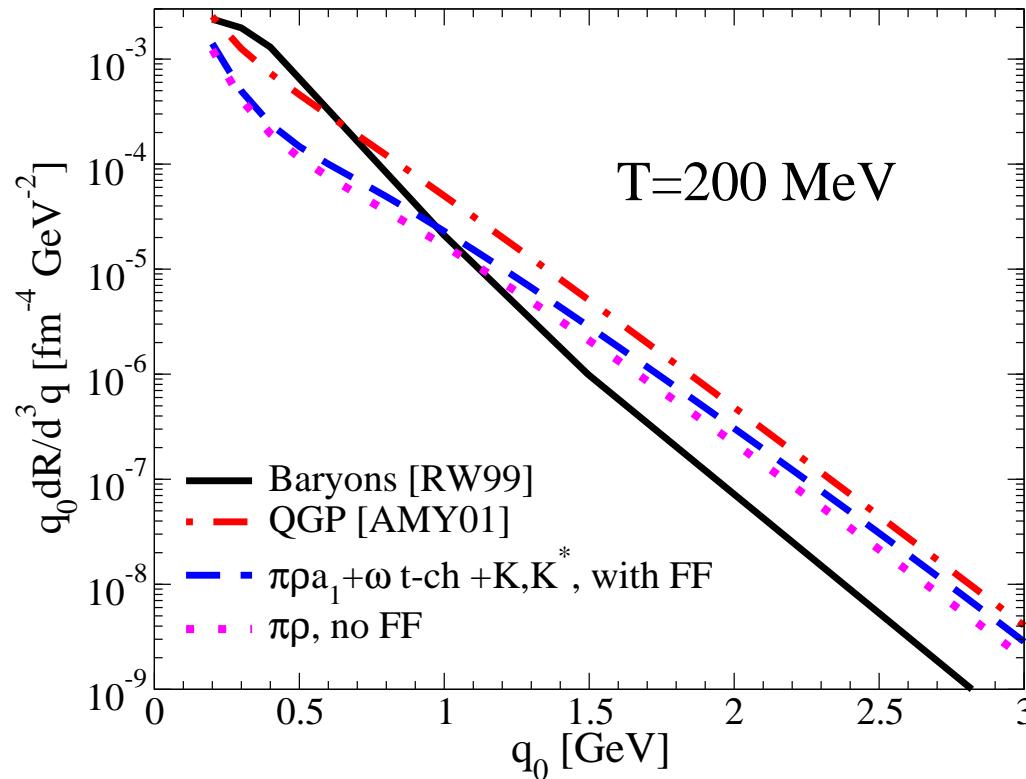
$$\begin{aligned}\mathcal{L}_{\text{eff}} = & \frac{1}{8}F_\pi^2 \text{Tr} D_\mu U D^\mu U^\dagger + \frac{1}{8}F_\pi^2 \text{Tr} M(U + U^\dagger - 2) \\ & - \frac{1}{2} \text{Tr} (F_{\mu\nu}^L F^{L\mu\nu} + F_{\mu\nu}^R F^{R\mu\nu}) + m_0^2 \text{Tr} (A_\mu^L A^{L\mu} + A_\mu^R A^{R\mu}) \\ & + \gamma \text{Tr} F_{\mu\nu}^L U F^{R\mu\nu} U^\dagger - i\xi \text{Tr} (D_\mu U D_\nu U^\dagger F^{L\mu\nu} + D_\mu U^\dagger D_\nu U F^{R\mu\nu}) .\end{aligned}$$

In the above,

$$\begin{aligned}U &= \exp \left( \frac{2i}{F_\pi} \sum_i \frac{\phi_i \lambda_i}{\sqrt{2}} \right) = \exp \left( \frac{2i}{F_\pi} \phi \right) , \\ D_\mu U &= \partial_\mu U - ig_0 A_\mu^L U + ig_0 U A_\mu^R , \\ A_\mu^L &= \frac{1}{2}(V_\mu + A_\mu) , \\ A_\mu^R &= \frac{1}{2}(V_\mu - A_\mu) , \\ F_{\mu\nu}^{L,R} &= \partial_\mu A_\nu^{L,R} - \partial_\nu A_\mu^{L,R} - ig_0 [A_\mu^{L,R}, A_\nu^{L,R}] .\end{aligned}\tag{2}$$

- all possible  $s$ -,  $t$ - and  $u$ -channel (Born-) graphs for:
  - $X + Y \rightarrow Z + \gamma$ ,
  - $\rho \rightarrow Y + Z + \gamma$ ,
  - $K^* \rightarrow Y + Z + \gamma$ .
- For  $X, Y, Z$  we have each combination of  $\rho, \pi, K^*, K$ .
- The  $a_1$  and  $\omega$  mesons included as exchanged particles.
- Form-factors are also included.
- All coupling constants adjusted to reproduce the mesons phenomenology.

# Photon production rate from different contributions



**Baryons** : R. Rapp and J. Wambach, Eur. Phys. J. A **6**, 415 (1999).  
**QGP** : P. Arnold, G.D. Moore and L.G. Yaffe, JHEP **0112**, 9 (2001).

- $a_1, K^*, \omega$  and FF increase bare  $\pi\rho$  without FF by  $\sim 40\%$
- Full hadronic and QGP results are close to each other around  $T = T_c$

## 1.b) Prompt photons

- use  $q_0 \frac{d^3\sigma_{\gamma}^{pp}}{d^3q}$  parametrization (D.K. Srivastava, Eur. Phys. J. C **22**, 129 (2001)).
- Must include Cronin effect :

Convolution of  $q_0 \frac{d^3\sigma_{\gamma}^{pp}}{d^3q}$  over a Gaussian distribution on  $k_T$

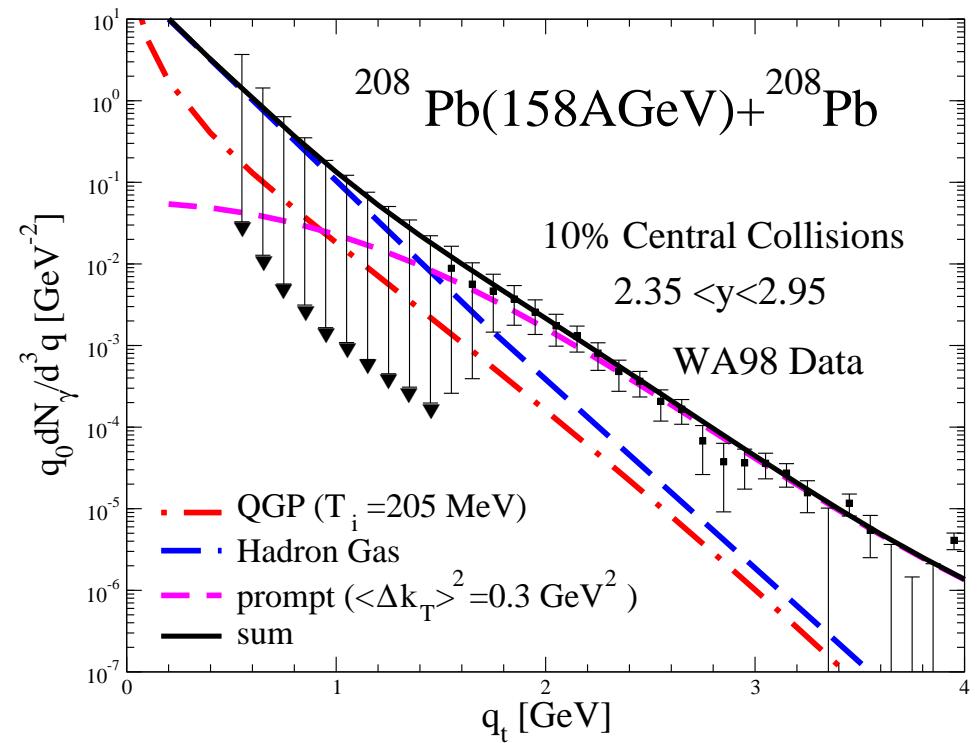
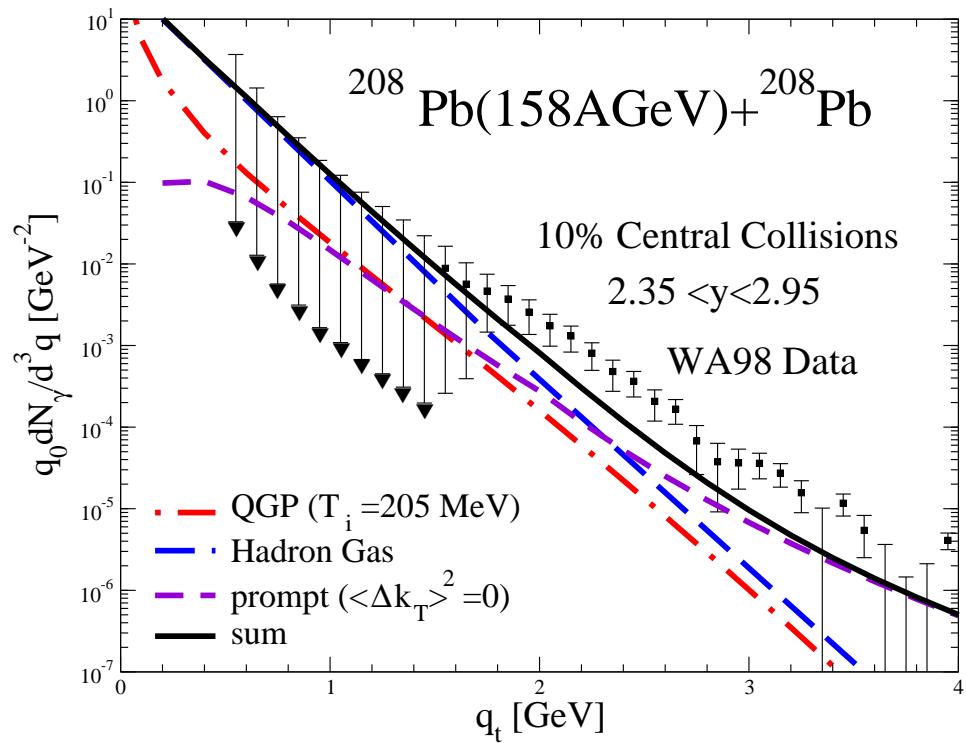
$$f(k_T) = \frac{1}{\pi \langle \Delta k_T^2 \rangle} e^{-k_T^2 / \langle \Delta k_T^2 \rangle}. \quad (3)$$

$$q_0 \frac{d^3 N_{\gamma}^{prompt}}{d^3 q}(q_T) = \frac{\langle N_{\text{coll}} \rangle}{\sigma_{in}} \int d\vec{k} f(k_T) q_0 \frac{d^3\sigma_{\gamma}^{pp}}{d^3q}(|\vec{k}_T - \vec{q}_T|) \quad (4)$$

$\langle \Delta k_T^2 \rangle \simeq 0.2\text{-}0.3 \text{ GeV}^2$  estimated by reproducing  $p\text{-}A$  collisions

# Photons at SPS

$$q_0 \frac{dN_\gamma}{d^3q}(q_t) = q_0 \frac{dN_\gamma^{prompt}}{d^3q} + \int dt V_{FB}(t) \left( q_0 \frac{dR^{\text{QGP}}}{d^3q} + q_0 \frac{dR^{\text{HG}}}{d^3q} \right), \quad (5)$$

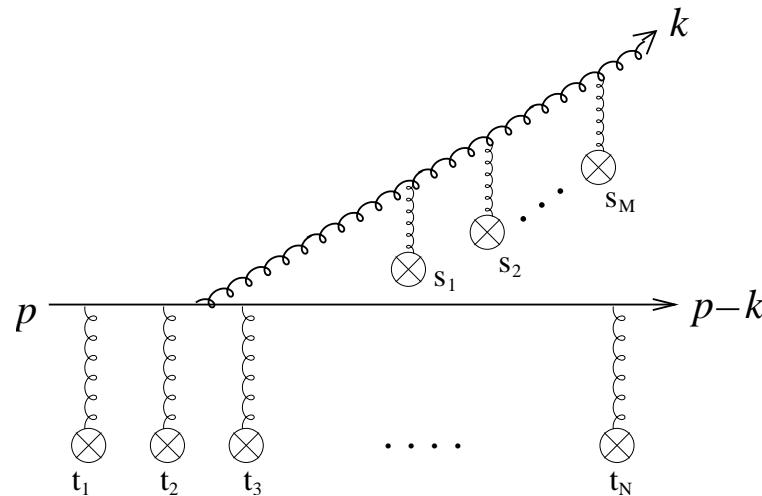


- QGP not necessary to successfully describe data

## 2. RHIC

**High- $p_T$  suppression:** in-medium induced gluon bremsstrahlung.

Typical diagram that need to be resummed:

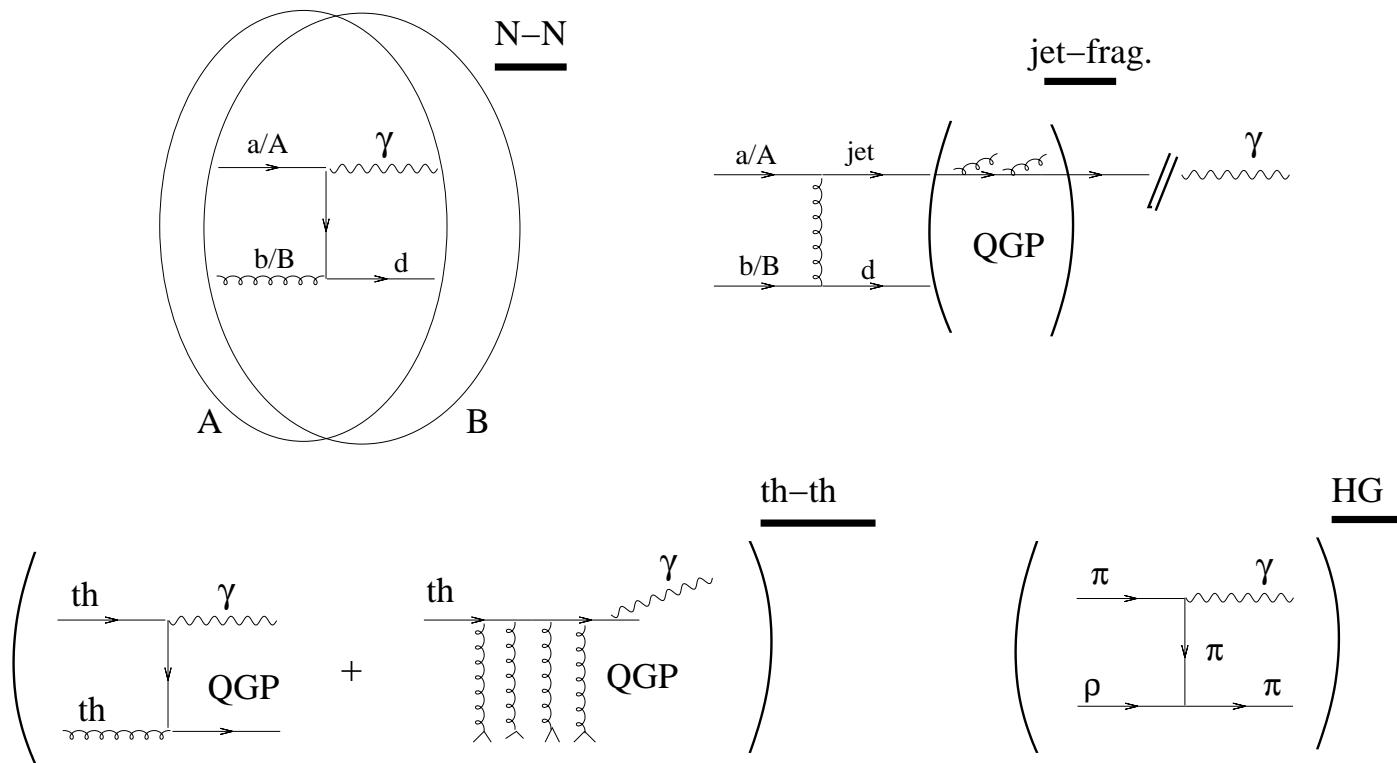


**Handled by the AMY formalism:**

P. Arnold, G.D. Moore and L.G. Yaffe, JHEP **0111**, 057 (2001).

- Complete leading order in  $\alpha_s$  treatment;
- Fully thermal calculations : scatterers are all dynamic;
- Absorption of thermal gluons and annihilation with thermal partons also included.

# Usual sources of high- $p_T$ photons.

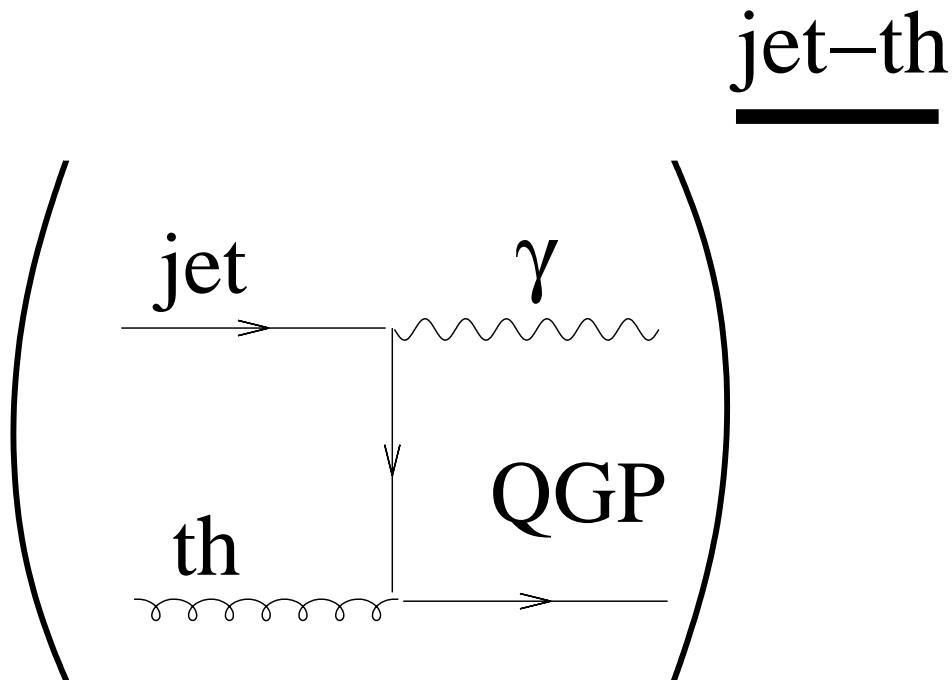


- High- $p_T$  suppression has to be included in the **jet-frag.** contribution.

# Additional sources of high- $p_T$ photons.

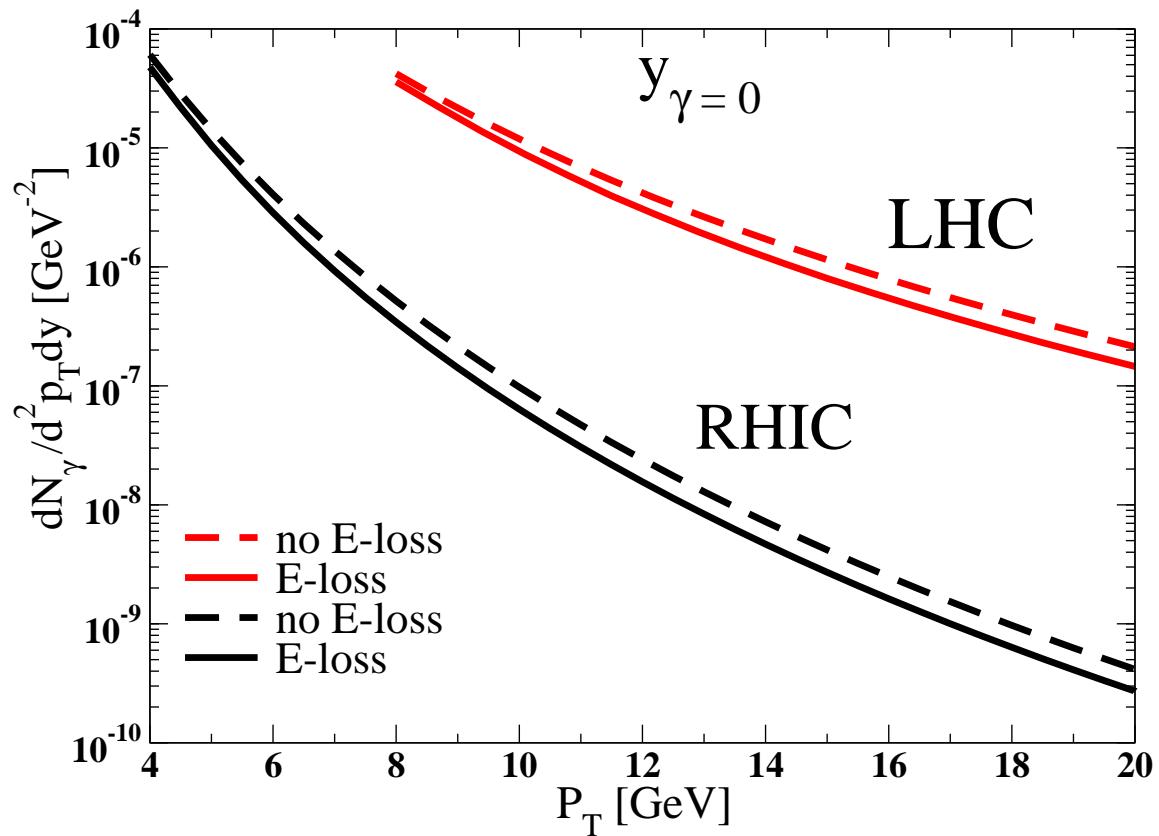
## Jet-photon conversion :

R.J. Fries, B. Müller and D.S. Srivastava, PRL 90, 132301 (2003).



- They find that process dominant for  $p_T \sim 4$  GeV;
- However, jet energy-loss has not been included.

# Effect of E-loss on jet-photon conversion

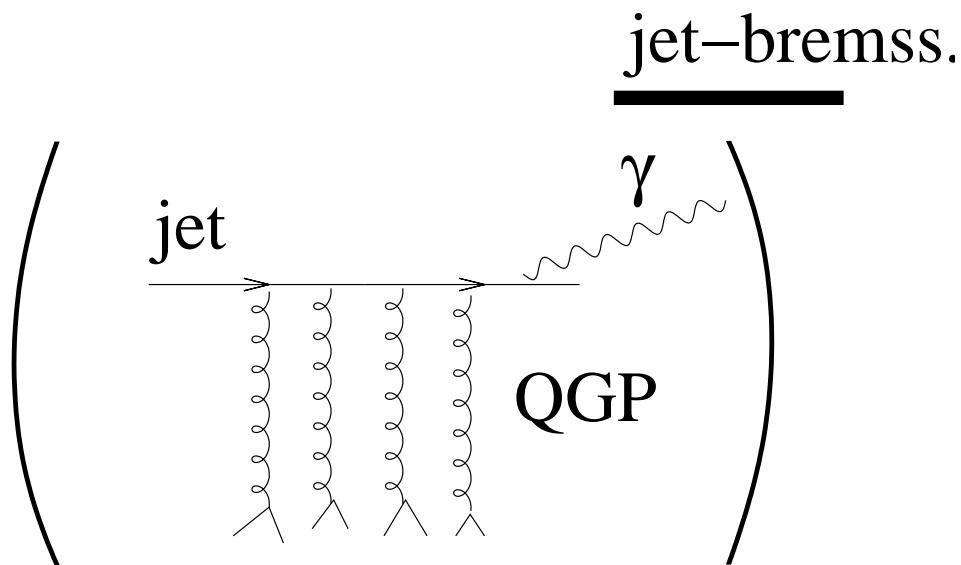


- E-loss effect : reduction factor  $R_\gamma \sim 1.4\text{-}1.6$

## 2.c) Additional sources of high- $p_T$ photons.

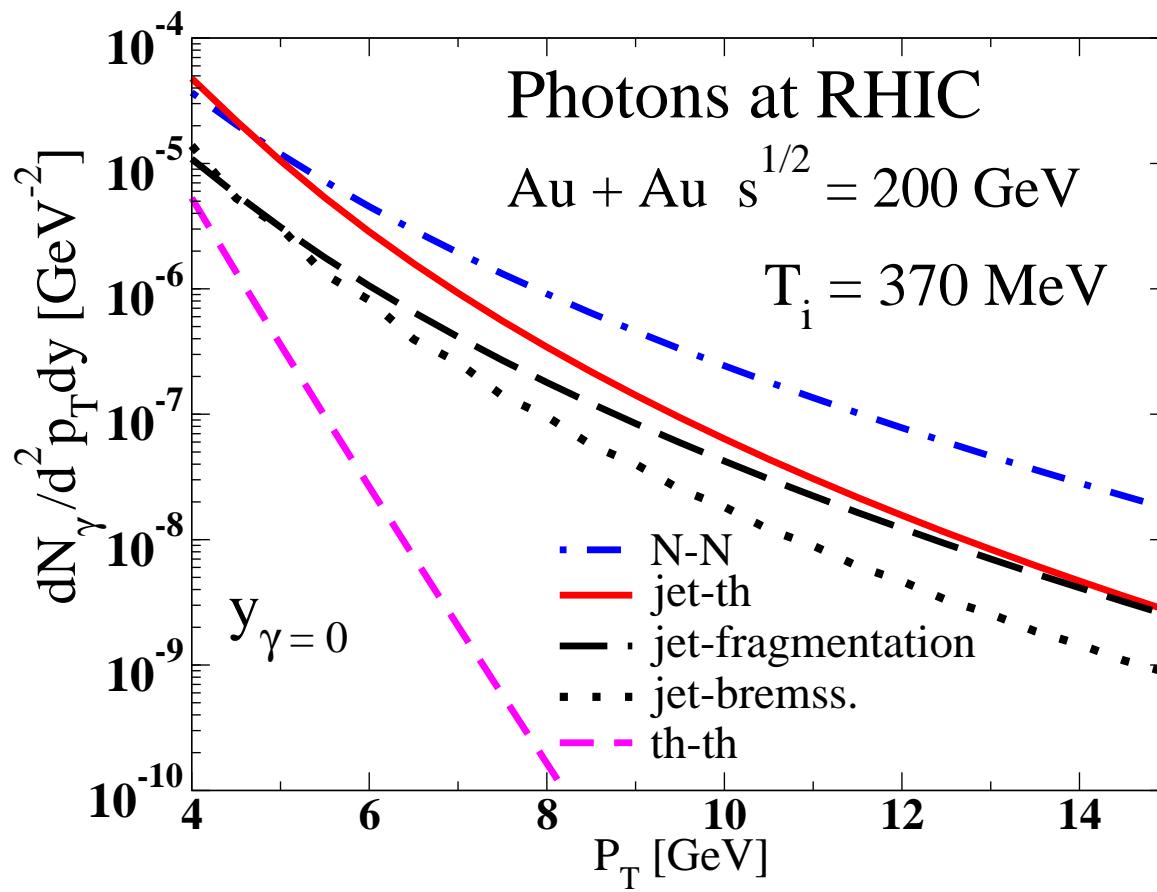
Jet-bremsstrahlung :

B.G. Zakharov, JETP Lett. 80,1 (2004).



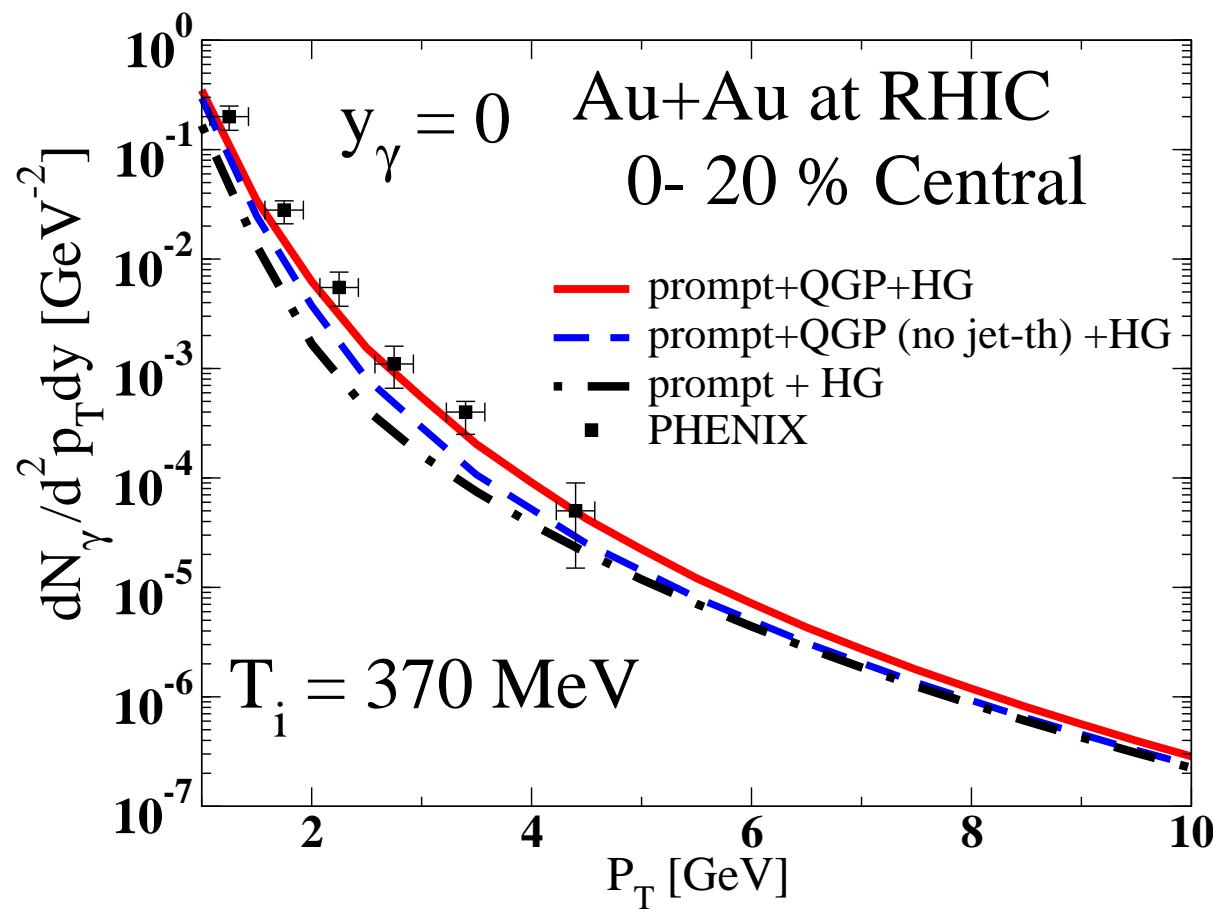
- can also be calculated with AMY formalism.

# High $p_T$ photon production: results



- E-loss effect doesn't rule out result of R. Fries *et al.* PRL 90, 132301 (2003): jet-photon conversion is still dominant for  $p_T \sim 4$  GeV.

# Compare with PHENIX



- jet-th increases total yield by a factor 2 around  $p_T = 3\text{GeV}$ ;
- QGP contribution turns out to be important for reproducing data.

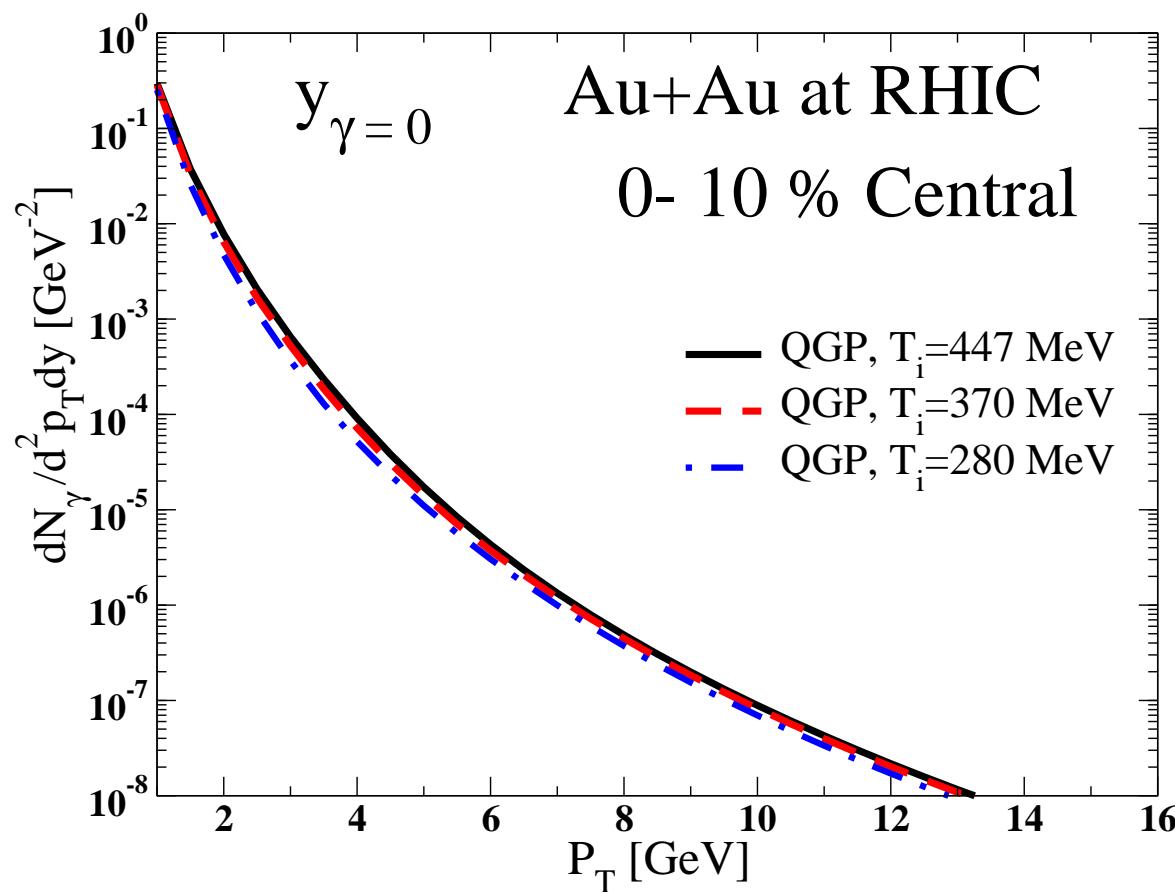
### 3. CONCLUSION

- New hadronic rates, including  $a_1, K^*, \omega$  and FF have been calculated, increasing bare  $\pi\rho$  without FF by  $\sim 40\%$ ;
- HG and prompt, with Cronin effect, are enough to describe SPS data;
- AMY formalism has been used for in-medium jet E-loss;
- even with E-loss, jet-photon conversion is the single most important process in the range  $2 < P_T < 4$  GeV;
- QGP turns out to give an important contribution at RHIC ( $1 < p_T < 6$  GeV).

**Thanks to the collaborators:** C. Gale, S. Jeon, G.D. Moore and R. Rapp.  
**References**

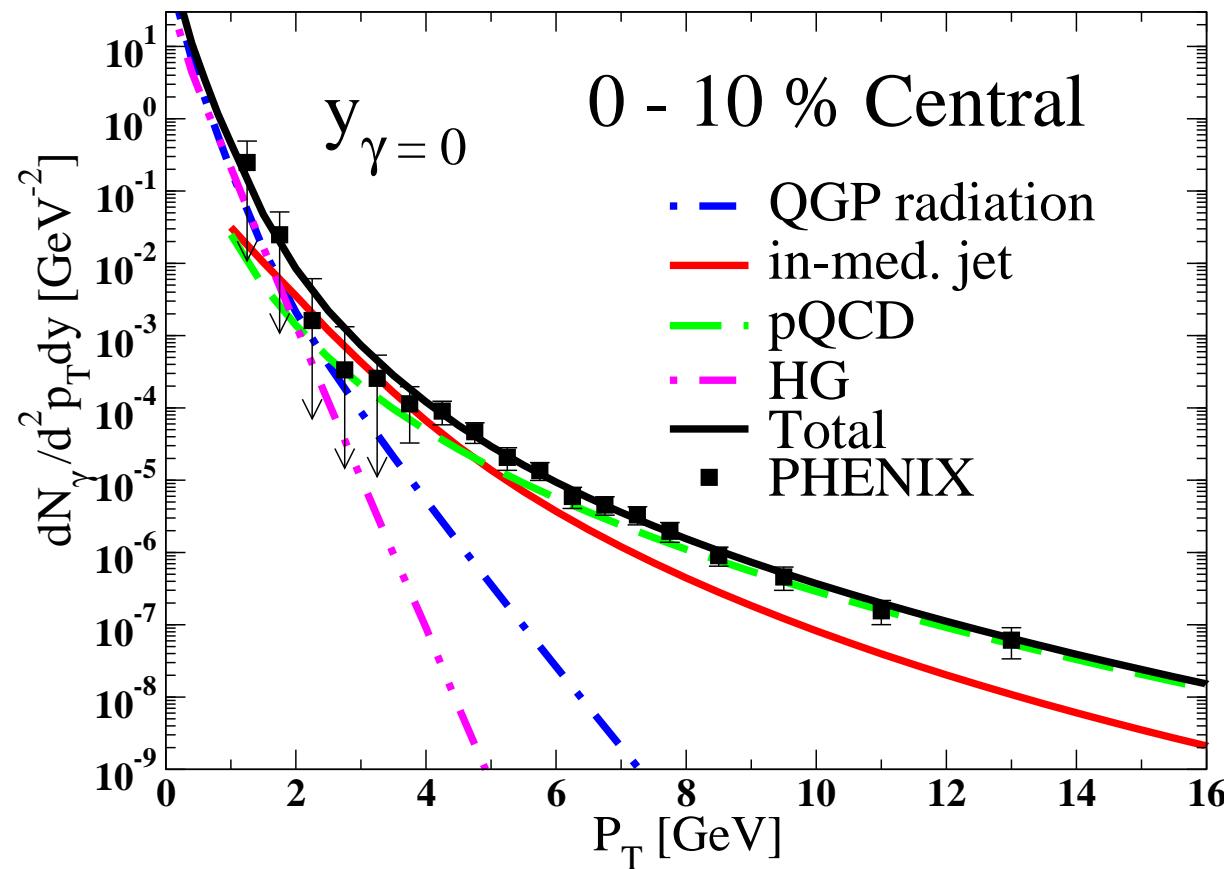
- S. Turbide, R. Rapp and C. Gale, Phys. Rev. C **69**, 014903 (2004);  
S. Turbide, C. Gale, S. Jeon and G.D. Moore, Phys. Rev. C **72**, 014906 (2005).

# Effect of initial conditions on thermal photons



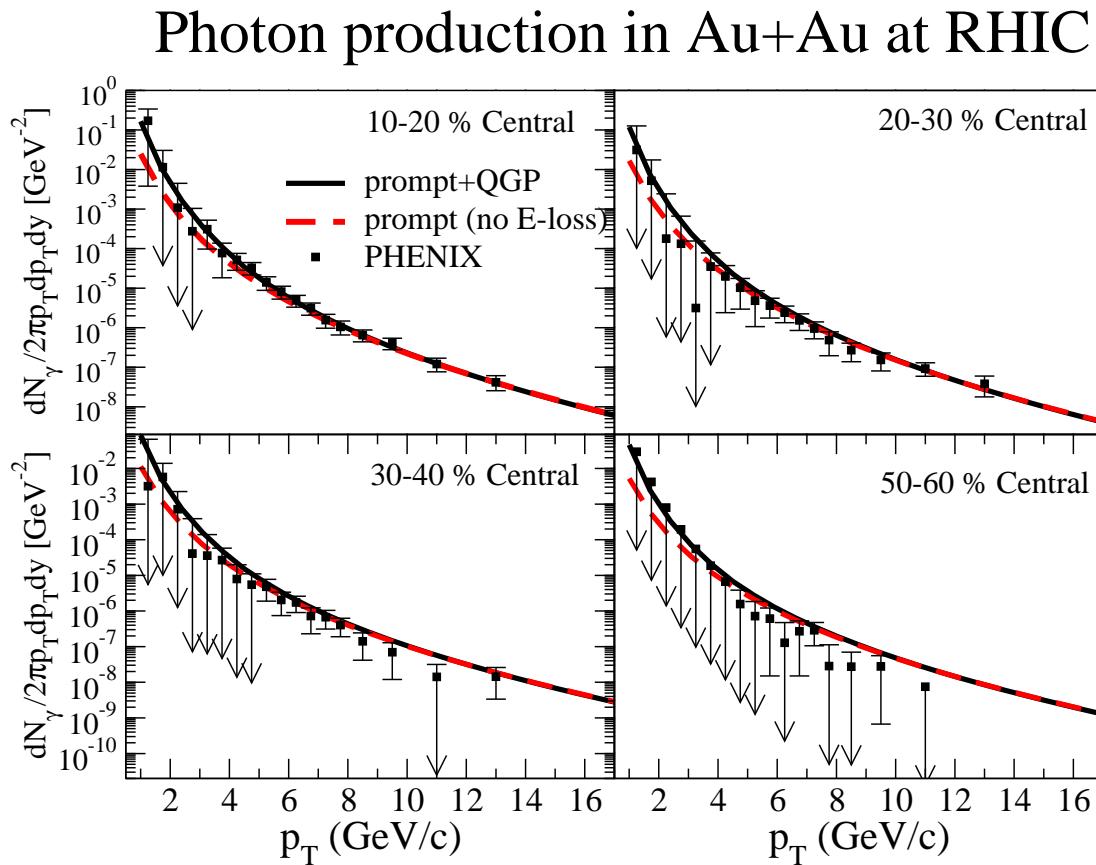
- Effect is small because thermal photons dominated by jet-th, which is not that affected by initial conditions.

## Au+Au at RHIC

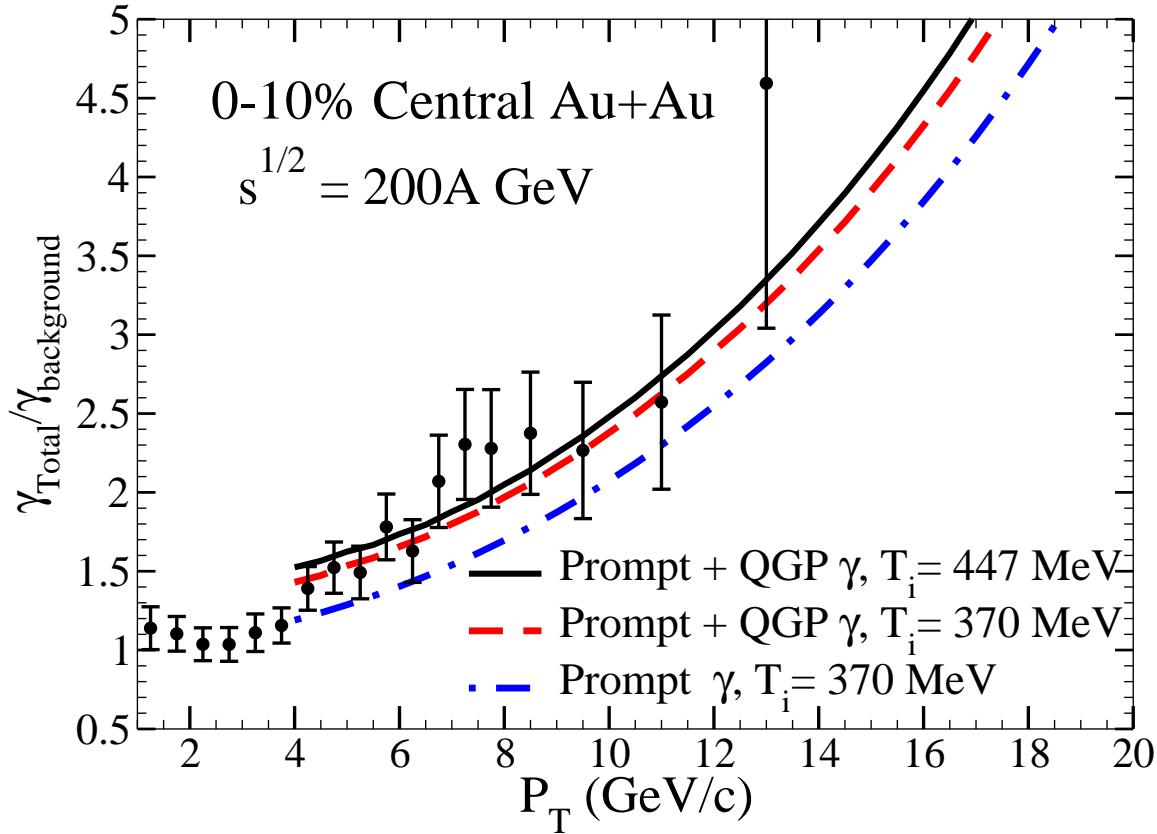


- Hadron gas and QGP radiation dominant for  $p_T < 2$  GeV.

# Calculations extended to non-central collisions

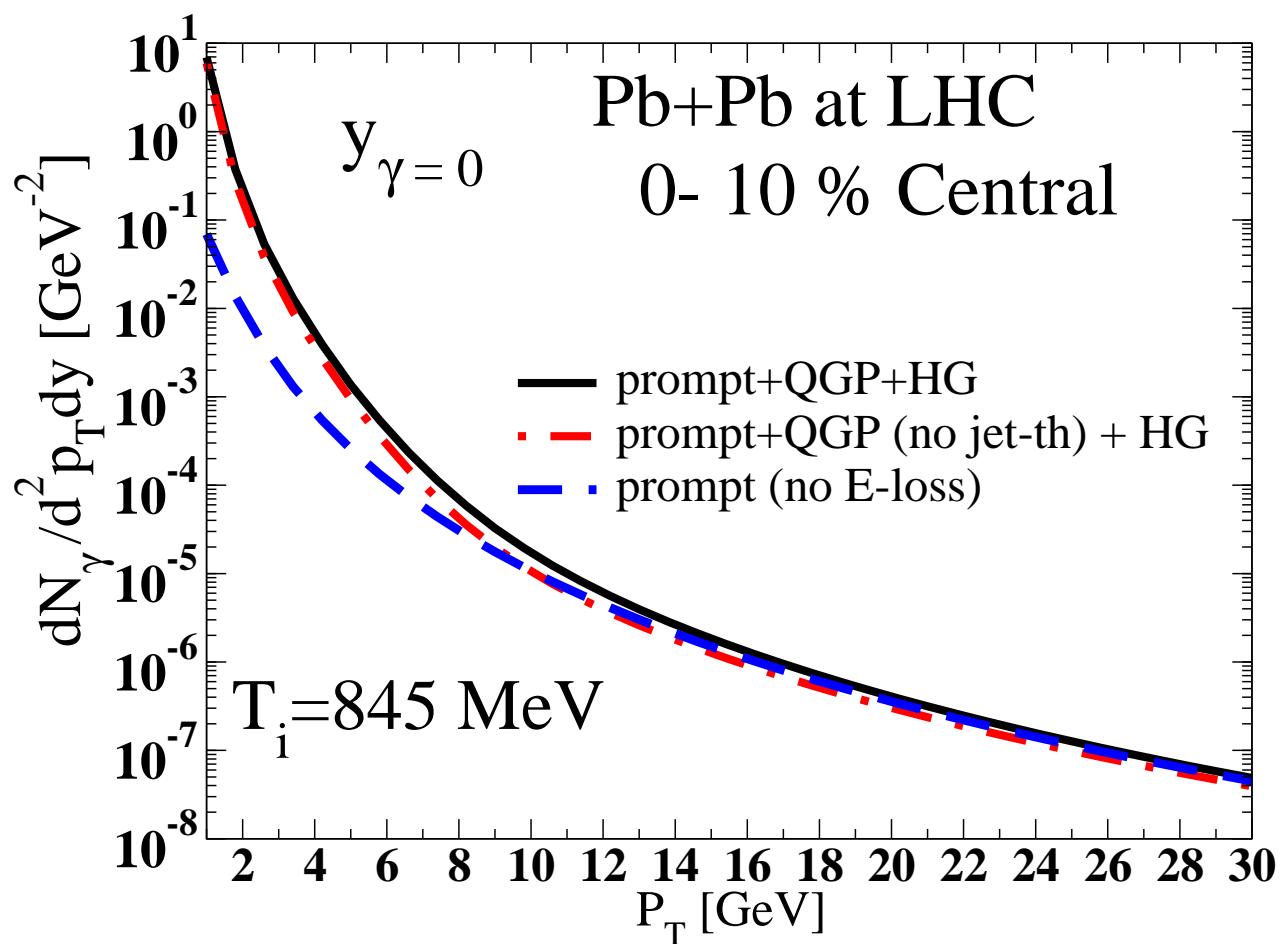


(All  $\gamma$ ) / ( $\pi^0 \rightarrow \gamma\gamma$ )



- QGP helps to be more consistent with data.

# Photons at LHC



# Effect of thermal radiation

$$R_{AA}^\gamma = \frac{dN_{AA}^\gamma|_{thermal} + dN_{AA}^\gamma|_{pQCD}}{dN_{AA}^\gamma|_{pQCD}} \quad (6)$$

